A COMPARATIVE STUDY OF DIGITIZED BRIGHTNESS AND 200-MB DIVERGENCE IN THE TROPICAL WESTERN NORTH PACIFIC

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THESIS

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DIGITIZED BRIGHTNESS AND 200-MB DIVERGENCE
IN THE TROPICAL WESTERN NORTH PACIFIC

by

Eriberto C. Varona

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Thesis Advisor: C.-P. Chang

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shown in the inter-longitudinal cross-spectra in the two bands, suggest that brightness is more organized than divergence, although the two fields resemble well each other whenever an organized divergence pattern is observed. Inter-parameter cross-spectra and correlation results indicate a generally in-phase relationship. However, the coherence squares and correlation coefficients are lower than those found by Wallace (1971) for the 4- to 5-day waves using direct radiosonde data.

A Comparative Study of
Digitized Brightness and 200-mb Divergence
in the Tropical Western North Pacific

by

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Submitted in partial fulfillment of the
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ABSTRACT

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I. INTRODUCTION

Satellite photographs have revealed that much of the cloudiness in the tropics is in the form of large, connected masses of very bright clouds. These cloud masses consist of varied individual cumulus clouds. The extensive cirrus canopies observed on top of these cumulus clouds account for most of their brightness, and may last a few hours longer than the cumulus cells themselves. These "cloud clusters," as they are now called, have attracted a great deal of attention for the past few years since, hypothetically, they play an important role in the general circulation of the atmosphere and in the formation of tropical storms. Chang (1970) and Wallace (1971) observed that many of the cloud clusters in the tropical Pacific are well organized and have characteristics which resemble those of synoptic-scale, westward propagating wave disturbances. Sikdar and Soumi (1971) and Reed and Recker (1971) found evidences that these cloud clusters are envelopes of deep convection in regions of organized upward vertical motion associated with synoptic-scale waves. Sikdar and Soumi (1971) further suggested that the deep convection cells tend to concentrate in a small area and are generally located in the geometrical center of the cloud cluster; moreover, they postulated that the time variations of these

cells could be excellent indicators for the convective energy transport to the tropical upper troposphere. Williams and Gray (1973) and Yanai et al (1973) also indicated that the active cloud clusters exhibit vertical characteristics similar to those found by Reed and Recker (1971).

The paucity of meteorological stations in the vast tropical oceans accentuates the imperative for further exploiting the utilization potential of available satellite data as aids in tropical analysis. In particular, because of the relationship between cloud cluster and synoptic-scale tropical motions, the digitized cloud brightness data[1] present a prime research area for such a purpose.

The physics of the atmosphere suggests a close relationship between digitized satellite cloud brightness (hereafter referred to, for brevity, as brightness) data and the large-scale vertical motion field. Williams and Gray (1973) pointed out that the cumulonimbi do serve as agents in the production of the large, bright cirrus canopies of the cloud clusters, with the developing and conservative clusters generally capable of maintaining their cumulonimbi in the presence of a steady low-level mass convergence, otherwise they gradually die out. Since low-level moisture over the oceanic tropics is readily available, the large-scale upward

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[1]Digitized brightness data have been made available since 1967, through the Advanced Vidicon Camera Systems of operational satellites.

motion provides a favorable environment for the development and maintenance of these clusters. Furthermore, the brighter clouds are usually thicker and, therefore, may indicate a larger amount of latent heat release (Gruber, 1974). Since deep tropical systems are characterized by temperature fluctuations which, by and large, are one order of magnitude less than the rate of latent heating, thermodynamic energy balance requires that the large-scale vertical motion be approximately proportional to heating [Wallace (1971) and Holton (1972)]. *A priori*, therefore, a positive correlation between brightness and large-scale vertical motion may be expected by reason of heating alone.

In fact, indications of good correspondence between area-averaged brightness and synoptic-scale vertical motion associated with the 4- to 5-day tropical waves in certain sections[2] of the tropical western North Pacific has been found by Wallace (1971), on which basis he postulated that the entire vertical motion field over large tropical areas may be estimated from satellite data alone. If this is the case, brightness is certainly one of the best available indicators of tropical weather disturbances considering that, at present, there is no direct way of obtaining a reliable vertical motion field in the data-sparse tropical regions.

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[2] These are in the Kwajalein-Eniwetok-Ponape (KEP) triangle of the Marshall Islands and the Guam-Truk-Yap (GTY) triangle farther west.

The correspondence between brightness and vertical motion may also be extended to large-scale horizontal divergence at levels where divergence is large, since several observational studies [Wallace (1971), Reed and Recker (1971), Nitta (1972), Williams and Gray (1973), and Yanai et al (1973)] indicated similar profiles of the vertical motion or divergence field over convectively active tropical areas. Implicitly, the same conclusion can be drawn from the vertical profiles shown by Hayashi (1974) from analysis of tropical output from the general circulation model of the NOAA Geophysical Fluid Dynamics Laboratory at Princeton. This is also consistent with the results of the composite study of Williams and Gray (1973), which show a clear in-phase relationship between cloud clusters and upper-level divergence. If satellite data could be used as a crude representation of the upper-level divergence, such data may be very useful in large-scale analysis over data-sparse tropical regions, particularly so when we consider that the upper-level circulation pattern is largely controlled by the strong divergence near the 200-mb level. By use of the quasi-barotropic property of the large-scale tropical flow, it may be possible to utilize the divergence information that could be inferred from the brightness data as a diagnostic tool in examining the flow pattern near the strong divergent level in a manner similar to Holton and Colton's (1972) model for seasonal mean motions.[3] With infrared (IR) radiation data, supplied by the

[3] A diagnostic model of using brightness as an aid for large-scale tropical flow is discussed in Jacobs (1974).

recently developed satellites, the possibility of representing the divergence field by brightness has increased. This is seen from the fact that one can determine cloud-top temperatures from IR data. These cloud-top temperatures, which are indicative of the vertical extent of cumulus development, can then be used to calculate the resulting latent heat release [Koffler et al (1973) and Rao (1970)]. Thus, it is possible to modify the brightness field and improve the estimate of the upper-level divergence (and vertical motion) field. Motivated by these considerations, this study seeks to extend the investigation of Wallace (1971) on the relationship between brightness data and upper-level divergence over a broader geographical area. In this study, we hope to find out the extent to which the current brightness data can be used to represent the synoptic-scale divergence in the tropical upper troposphere. In so doing, both spectral and correlation analyses are used.

The main reason for performing spectral analysis is because of the importance of synoptic-scale tropical disturbances which may highly influence the variations in both the divergence and brightness fields. These variations may be characterized by certain dominant time scales associated with synoptic-scale disturbances which may or may not be related to the easterly waves. It is the interest of this study to determine how the behavioral characteristics of these two parameters resemble each other in synoptic time scales.

Several spectral studies of tropical cloud brightness [Tanaka and Ryuguji (1971, 1973), Murakami and Ho (1972a, 1972b), Wallace (1971), Sikdar et al (1972), and Wallace and Chang (1972)] have been carried out previously. While some of these spectral studies yielded interesting results, Wallace and L. Chang (1972) suggested that the number of spectral peaks revealed by these studies are so numerous that, invariably, it would be extremely difficult to extract significantly useful information from such results. They also pointed out that the power spectra of brightness are highly variable in both space and time, and even neighboring grid points may exhibit quite different characteristics. However, the main purpose of the spectral analysis in this study is not to identify tropical wave disturbances as had been done in other studies. The purpose in this case is simply to use the spectral analysis technique as a convenient tool to decompose both brightness and divergence into their various time scales that are of synoptic interest in the period of this investigation. In addition, correlation analysis is applied, mainly to determine the daily spatial relationship, as well as to complement the cross-spectral analysis of the time series of both fields.

II. DATA AND METHODS OF ANALYSIS

A. DATA

The brightness and upper-level wind data used in this study were provided by the National Center for Atmospheric Research (NCAR). The brightness data, acquired by NCAR from the National Environmental Satellite Service, are digital values representing variations from total absorption (0) to total reflection (10) of solar radiation in the visual channel. These digitized values are averaged for 5° x 5° latitude-longitude squares and adjusted for instrumental and calibration errors (Gray and Oort, 1974). The upper-level wind components (u, v), which were used to generate the divergence time series, were acquired by NCAR from the National Meteorological Center tropical grid analyses. These winds are given at grid points approximately coinciding with those for the brightness data, and are the result of analyses based on all available rawinsonde records, aircraft observations, and a few data deduced from cloud drift as seen from satellite photographs. The 0000 GMT wind data are considered to be closest to (within 2 to 3 hours of) the satellite observation time.

The divergence field for the upper levels was derived directly from the horizontal wind components without any adjustment by vertical boundary constraints. Maximum divergence

was found at the 200-mb level, consistent with the previous divergence profiles found by Wallace (1971), Reed and Recker (1971), Williams and Gray (1973) and others. In these profiles, the levels of maximum divergence are near 200 mb, indicating that this is generally the outflow level of tropical motion systems associated with cloud cluster activities.

Missing data were filled by a combination of simple and quadratic interpolation in time and a 4-point averaging in space. The projected values were restricted within the maximum and the minimum of the observed field.

The general area selected for this study is the tropical western North Pacific from the Equator to 25N and from 125E to 175E. There are two reasons for this choice. Firstly, previous studies indicated that this is an area of strong cloud cluster activity. Secondly, the analyzed wind data in this region are more reliable than those in other tropical locations because of the relatively denser rawinsonde network. Figure 1 shows this observational network in the region of investigation.

The period of observation is approximately eight months, 19 April - 20 December 1971. This period was chosen because daily records of IR radiation are available for the first 83 days, namely: 19 April - 10 July 1971; hence, further investigation using IR-modified brightness could be pursued to shed additional light on the findings of this study. This is possible because, as mentioned in Section I, cloud-top

temperatures and cloud-top heights or the vertical extent of cumulus development can be estimated from the known IR field. Such estimates may then be utilized to modify the brightness pattern and, consequently, improve its correlation with that of the upper-level divergence or vertical motion.

B. SPECTRAL ANALYSIS

The BMD02T portion of the UCLA Biomedical Statistical Program Package was used for power spectral (and the associated cross-spectral) analysis. Both the brightness and divergence time series were first subjected to a high-pass filter which is described in Part D of this Section. A 20-day lag was used, which gives a frequency bandwidth of 0.05 cycle day^{-1} (cpd) and a frequency limit of 0.5 cpd [Bendat and Piersol (1971), Panofsky and Brier (1965), Jones (1964), and Blackman and Tukey (1958)]. Spectral information is then given at a frequency interval of 0.025 cpd.

Coherence squares, as listed in Tables I and II, represent averaged values within each of the two dominant frequency bands, namely: 0.075 - 0.125 cpd (8.0 - 13.3 days) and 0.175 - 0.225 cpd (4.4 - 5.7 days), hereafter referred to simply as the 10-day and 5-day period bands, respectively. The phase differences were realistically chosen to be representative (i.e., consistent phase differences produce a nearly average phase estimate, as used in previous studies) of each band in question.

To analyze the coherence square results, the question of statistical significance was resolved by taking into account that averaging the spectral estimates over three consecutive frequencies would amount to doubling the number of degrees of freedom implied by the individual spectral calculations. Consequently, in estimating the significant values at the levels indicated, the coherence square probability distribution as compiled by Amos and Koopmans (1963) was used.

C. CORRELATION ANALYSIS

To complement the spectral analysis technique, correlation analysis was conducted, using the BMD02D of the aforementioned Statistical Program Package. The unfiltered data (as space and time series) of brightness and 200-mb divergence were subjected to correlation analysis.

The space series cross-correlation analysis involved 66 pairs of observations each day; this was done on a daily basis from May to October, which are considered as the summer period in the tropics. The time series, on the other hand, consisted of 246 pairs of observations for each of the 66 grid points. In both cases, the significant correlation coefficients, as listed in Tables III and V, were determined following Panofsky and Brier (1965).

D. SPECTRAL FILTER

As cited earlier, before conducting the spectrum and cross-spectrum analyses, a high-pass filter is applied

following Holloway (1958). The filtering technique is quite similar to those utilized in other investigations [Murakami and Ho (1972), Yanai and Murakami (1970), Yanai et al (1968), and Maruyama (1968)]. A normalized Gaussian weighting function W_n with a standard deviation δ of 25/3 days is used, namely:

$$W_n = (2\pi\delta^2)^{-1/2} \exp(-t^2/2\delta^2)dt \ , \tag{1}$$

where $dt = 1$ day ,

$t = ndt$, and $n = 0 , \pm 1 , \pm 2 \ldots \pm 24$.

The frequency response of this weighting function effectively filters out (89% efficient) periods beyond 3δ or 25 days (Holloway, 1958). As seen in Figure 2, this spectral response is ideal for frequencies beyond 0.075 cpd or, equivalently, for periods not exceeding 13.3 days. Mathematically, this frequency response $R(f)$ is expressed as a function of the standard deviation δ and frequency f :

$$R(f) = 1 - R_o(f) \ , \tag{2}$$

where

$$R_o(f) = \exp(-2\pi^2\delta^2 f^2) \ . \tag{2a}$$

A weighted average is then calculated for every 49 (approximately 6δ) consecutive data of the original time series X_i of 246 days, thus resulting in a smoothed time

series $\bar{X}_i$ of 198 days.

Symbolically:

$$\bar{X}_i = \sum_{n=-24}^{24} W_n X_{i+m} / \sum_{n=-24}^{24} W_n \ , \qquad (3)$$

where $i = 1, 198$ and $m = 25$. The time series of the filtered data X_i' is then generated by the deviation of the smoothed time series from the observed time series, viz.:

$$X_i' = X_i - \bar{X}_i \ . \qquad (4)$$

III. RESULTS AND DISCUSSION

Before discussing the results of this study, it might be useful to realize that the techniques of spectral and correlation analyses can be interpreted as some means for understanding better those meteorological phenomena the physical nature of which are partially understood. Moreover, the results of these techniques should be considered not purely on a statistical basis but also on the premise that they are compatible with synoptic and dynamic considerations [Yanai and Murakami (1970) and Panofsky and Brier (1965)].

A. SPECTRAL AND CROSS-SPECTRAL ANALYSES

1. Power Spectra

Figures 3 and 4 show the power spectra at each of the 66 grid points for brightness and 200 mb divergence (div_{200}), respectively, as generated by (4). An examination of these spectra indicates that the two frequency ranges: 0.075 - 0.125 cpd (10-day period band) and 0.175 - 0.225 cpd (5-day period band), contain substantial segments of the total variances of each of the two series at most points. This means that during the period of this study, the divergence pattern at 200 mb associated with synoptic wave disturbances has characteristic time scales of 5 and 10 days. Hence, it is convenient to choose these two bands for

comparing the behavior of brightness and div_{200}. Although the main concern of this study is not to define the spectral peaks, it should be recognized, nonetheless, that most of the major peaks do fall into these two bands. In this context, it might be significant to recall that previous studies [Sikdar et al (1972), Murakami and Ho (1972), Tanaka and Ryuguji (1973) and Gruber (1974)] found similar 2-band structures in the spectra of tropical cloudiness. It is apparent then that while there is a high variability in the brightness spectra, simple interpretation of a 2-band distribution is quite consistent with several studies and should not be overlooked. Additionally, one can notice a tendency for a 3-day spectral peak to appear occasionally; however, the peaks seldom appear concurrently in both parameters and, further, the fraction of the total variance involved is relatively small in most cases.

2. Coherency and Phase

The coherence squares and the corresponding phase differences between brightness and div_{200} at each grid point, within each dominant frequency band, are listed in Tables I and II. The averaging process results in a degree of freedom of approximately 25, implying a significant coherence square of 0.17 at the 99% confidence level, 0.12 at the 95% level, and 0.09 at the 90% level. Only those values which are significant at the 90% level or better are tabulated. For the 10-day band (Table I), 24 grid points have significant

coherence squares, most of which indicate phase differences from in-phase to nearly 1/4 cycle between the two parameters. For the 5-day band (Table II), 20 points have significant coherence square values and, except for three points [(5N, 135E), (20N, 145E), and (20N, 150E)], there seems to be a similar relationship as in the 10-day band, although the larger (close to 1/4 cycle) phase difference is more common in the 5-day band. A relative comparison of these results for both frequency bands with those of Wallace (1971) for the 4- to 5-day waves indicate that, although the two parameters are much more in-phase than out-of-phase in this study, the coherence squares are somewhat lower and the phase differences are slightly larger. The reason for this difference could be explained in the light of the following: (a) smoothed, analyzed winds were used for computing divergence in this study compared with the direct radiosonde data used by Wallace (1971), (b) Wallace used a vertical motion field which was kinematically calculated from a vertically adjusted divergence field, as compared with the non-adjusted divergence field in this investigation, and (c) the time difference between the two fields was ignored in this study.

3. Horizontal Structure

Another indication of correspondence between the two parameters in the 10-day and 5-day bands may be found by comparing the horizontal structures deduced from inter-longitude

cross-spectra for both parameters at each latitude, as shown in Figures 5-6. For each latitude, the 150E series is used as the base series to cross with other series at the same latitude. Each phase difference is plotted against the longitudinal distance from the base series and, unless the points are widely scattered, a best fitting line is drawn for each latitude weighted by the confidence level of the coherence square associated with each phase value. This technique has been commonly used in spectral wave studies for determining wavelengths and propagating directions.

For the 10-day band (Figure 5), a westward movement in the brightness data with an apparent "wavelength" of about 50° (5600 km) could be inferred at all latitudes except the Equator, suggesting a "phase speed" of nearly 5° day^{-1}. This simple interpretation, however, seems to be inapplicable in the eastern portion of 10N and 25N, and the easternmost part of 20N. Further, one may take note that the brightness field is more organized than the divergence field where the brightness results are best, viz.: 5N, 15N, and 20N. It seems significant to note, moveover, that another similarity can be found at 10N, where an in-phase relationship is observed for the divergence series between 140E and 175E, and the brightness series between 145E and 170E. These results may be indicative of an east-west orientation and suggest the presence of an Intertropical Convergence Zone (ITCZ) with intensity fluctuating around a period of approximately 10 days.

The structures of the 5-day band (Figure 6) seem to be less regular compared to those of the 10-day band, with the divergence, again, less organized than the brightness. One may take not also that a partial best fitting line, at least, could be drawn for brightness at all latitudes, although the "wavelength" ranges from about 25° (2800 km) at the northern latitudes to nearly 50° (5600 km) at the southern latitudes, thus indicating a "phase speed" range of approximately 5° to 10° day^{-1}. It might be of interest to note further that only two organized patterns, at 5N and 20N, may be observed for the divergence but, in each case, agree well with those of their respective brightness fields. The fact that the brightness pattern is more organized than the divergence field, as revealed in the inter-longitude cross-spectra indicated in Figures 5 and 6, reaffirms our belief that brightness is qualitatively better than divergence.

A similar attempt was made to make reasonable inferences from the inter-latitude cross-spectra, however, no significant interpetation could be deduced because of the low coherences found in most cases.

B. CORRELATION ANALYSIS

1. Correlation of Space Series

The daily correlation coefficients of brightness *versus* div_{200} as a function of space (unfiltered data) is listed in Table III for the tropical summer, i.e., May - October 1971. The sample size is 66, implying a signficant

correlation estimate of ≥ 0.24 for the 95% confidence level, and ≥ 0.20 for the 90% level (Panofsky and Brier, 1965). It is interesting to note that of the 167 days with useful data[4], 56 days (33.5%) indicate positive correlation at the 90% level or better while nine days (5.4%) tend to show a negative correspondence. These results which, by and large, are similar to the findings for July 1969 (Edwards, 1973) suggest a weak positive correlation between the two fields on a daily basis[5]. One may notice, likewise, that for the "wet" months (July - October), of the 109 days with useful data, 42 days (38.5%) show positive correlation while 5 days (4.6%) indicate negative correlation. On the other hand, out of 58 useful data for the relatively "dry" months of May and June, 14 days (24%) show positive correlation and 4 days (6.9%) indicate negative correlation. These comparative results appear quite consistent with the prevailing theories on the correspondence between precipitation and areas of low-level convergence or upper-level divergence. [See for example: Holton (1971) and Palmen and Newton (1969).] It should be realized, however, that these correlation coefficients are somewhat low as compared to those (inferred from the coherence squares) observed

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[4]Correlation estimates for which brightness and/or wind components (used to derive the divergence field) were originally missing were discarded.

[5]Because of the many uncertainties in the computed divergence, the positive correlation listed in Table III (and Table V discussed in the next Section) should not be viewed as equivalent to the probability of finding a positive correlation between brightness and the actual 200-mb divergence at a given time (or space).

by Wallace (1971) for the 4- to 5-day waves at the KEP triangle, although they do indicate a tendency of in-phase relationship between the two parameters on a daily basis. Besides the possible errors involved in the kinematic computation of divergence and the time difference between the two fields, it is evident that the correspondence between the two fields is far from perfect.

Moreover, it may be expected that the days of positive spatial correlation is partially due to the presence of strong convective systems. Table IV is a comparison of the frequency of positive correlation (Rf) between brightness data and 200-mb divergence with the frequency of tropical storms (Sf) in the region of study from May - October 1971, which shows a nearly constant Rf to Sf ratio. However, it must be realized that usually tropical storms occupy only one grid point (horizontal scale ~ 5°) at any one time.

2. Correlation of Time Series

The correlation coefficients between the time series of the two parameters under study (Table V) were similarly computed at all the 66 grid points in order to examine their spatial distribution. The sample size is 246 (unfiltered data covering the period 19 April - 20 December 1971), resulting in a significant correlation estimate of ≥ 0.12 at the 95% confidence level, and ≥ 0.10 at the 90% level. For the entire region, 25 points (37.9%) indicate positive correlation at the 90% level or better, while 3 points (4.5%) show

an apparent negative correlation. These results appear to be compatible with the daily computations discussed earlier and, likewise, are comparatively lower than the results found by Wallace (1971). We do notice, however, that the three negative correlations are in the southeast corner of the region and that all the interior points indicate positive relationship. Edwards (1973) examined the relationship between brightness and vertical motion for the July 1969 data and found that the correspondence between the two fields is quite irregular in the eastern portion of the region. He suggested that this may be mainly due to the relatively weak cloud cluster activities in that area. Thus, if the region of study were narrowed to the area bounded by 135E and 160E, from the Equator to 20N, the daily correlations would be much higher.

IV. SUMMARY AND CONCLUSION

In summary, this study is an attempt to investigate the temporal and spatial relationships between digitized brightness data and 200-mb divergence, as derived from the analyzed wind field, over a broad tropical region, namely: from the Equator to 25N, and from 125E to 175E. Spectral analysis was utilized to determine the dominant synoptic time scales for both parameters during the period 19 April - 20 December 1971. To complement this technique, correlation analysis was applied at all the 66 grid points between the time series of each parameter for this ~ 8 month period, and on a daily basis during the tropical summer: May - October 1971.

Two common period bands, one centered near 10 days and the other near 5 days, have been observed. The cross-spectra between the digitized brightness and 200-mb divergence indicate a generally in-phase (< 1/4 cycle) relationship in these two bands, and further that the coherence squares are somewhat lower and the corresponding phase differences are slightly higher than those found by Wallace (1971) for the 4- to 5-day waves using direct radiosonde data. The horizontal structures of both parameters, as revealed by the inter-longitude cross spectra in the two bands, suggest that the brightness pattern is much more organized than that of the divergence. It is apparent, however, that the two fields resemble each other

whenever an organized pattern in the divergence can be found. Moreover, the zonal structures are less regular in the 5-day band than in the 10-day band. In addition, there is an indication of a "wavelength" of approximately 5600 km for the 10-day band and 2800 to 5600 km for the 5-day band, or a "phase speed" of about 5° day^{-1} and 5° to 10° day^{-1}, respectively. Correlation results for the space series suggest a relatively weak positive relationship between the two fields on a daily basis, and are consistent with the results for the time series. A somewhat higher correlation is found during the wet months of July - October than in the relatively dry months of May and June.

The correspondence between the current brightness and divergence data as indicated in both the spectral and correlation analyses is far from perfect. However, in their entirety, the various results of this study do form a picture of positive relationship between the two fields. Thus the prospects of estimating the large-scale convection (vertical motion or divergence) field over a broad tropical region by the use of satellite data, as proposed by Wallace (1971), appear bright. Such estimates are believed to work best in areas of pronounced convective activity because of the expected influence of the presence of strong convective systems. Moreover, until the present brightness data can be improved upon they are more useful in tropical wave studies than direct operational applications. The statistical results

of this study tend to support this point of view. For example, it was shown that the digitized brightness data reflect quite well the upper-level divergence pattern associated with synoptic-scale disturbances. Hence, it may be used to investigate the upper-level heating patterns since, by thermodynamic considerations, divergence is mainly related to heating in the tropical upper troposphere.

Evidently the divergence data (as calculated from the smoothed, analyzed winds) contained several errors and, thus, might have reduced the correlation between brightness and divergence in this study. However, obtaining better divergence values from wind reports presently available in the tropics is conceivably difficult unless the observational network in the area is improved. This is precisely the very reason for current attempts to exploit the maximum utilization of satellite data. Also, problems do arise in utilizing brightness data to represent heating due to cloud cluster convections. Hopefully, these problems may be lessened by the availability of IR data which may be used to enhance the brightness data. The reason is primarily that the vertical extent of cumulus development can be determined from the IR information. Thus, an investigation on the relationship between IR-modified brightness and divergence is recommended.

TABLE I

Cross-spectra between brightness and 200-mb divergence for the 10-day band for 19 April - 20 December 1971. At each grid point, the upper value is coherence square (in hundredths) and the lower value is phase difference (in hundredths of a cycle). Values shown in parentheses are significant between the 90% and 95% confidence lvels; values shown without parentheses are significant at the 95% level or better.

Lat./Long.	125E	130E	135E	140E	145E	150E	155E	160E	165E	170E	175E
25N	-	-	-	-	-	-	-	-	-	-	-
20N	(11)/-05	(10)/-08	-	-	14/-13	-	-	(10)/29	-	-	-
15N	(10)/-04	-	-	(10)/12	16/12	-	-	-	(10)/-01	(10)/05	-
10N	-	16/24	-	13/18	12/-30	(10)/-17	15/07	-	-	-	-
5N	-	-	-	24/03	15/10	(11)/10	-	(11)/05	12/-03	13/16	14/08
Equator	-	-	14/20	20/12	15/19	-	-	-	-	-	-

TABLE II

Same as Table I except for the 5-day band.

Lat./Long.	125E	130E	135E	140E	145E	150E	155E	160E	165E	170E	175E
25N	-	-	$\frac{24}{20}$	-	-	-	-	-	-	-	$\frac{(10)}{-04}$
20N	-	$\frac{(10)}{02}$	-	-	$\frac{(11)}{-33}$	$\frac{(11)}{-34}$	$\frac{14}{-20}$	$\frac{(11)}{-22}$	$\frac{(10)}{-18}$	-	-
15N	-	$\frac{16}{-03}$	-	-	-	-	-	$\frac{14}{21}$	-	$\frac{23}{-09}$	$\frac{(10)}{-03}$
10N	-	$\frac{(11)}{13}$	-	-	-	$\frac{19}{03}$	-	-	-	-	$\frac{(10)}{-21}$
5N	-	-	$\frac{(10)}{35}$	-	-	-	-	-	-	-	-
Equator	-	-	$\frac{15}{14}$	$\frac{21}{22}$	$\frac{13}{25}$	$\frac{15}{26}$	-	-	-	-	-

TABLE III

Daily correlation coefficients (in hundredths) of satellite cloud brightness vs 200-mb divergence for May-October 1971. Values in parentheses are significant between the 90% and 95% confidence levels, and values without parentheses, at the 95% level or better. The letter "M" represents missing data for either or both the brightness and the wind field.

Day	May	Jun	Jul	Aug	Sep	Oct
1	27	-	(-21)	M	-	-
2	-	24	-	28	-	-
3	-	-	(-22)	(22)	-	-
4	26	-	-	29	-	26
5	-	-	-	28	26	M
6	-	-	-	-	-	-
7	35	-	(22)	-	M	-
8	-	-34	28	M	42	33
9	-	-	(22)	-31	(20)	-
10	(21)	-	-	-	34	36
11	-	38	32	-	-	34
12	(22)	45	38	-	-	(20)
13	-	32	30	-	M	M
14	-	-	34	-	-	M
15	33	-	-	-	44	M
16	-	-	-	-	52	M
17	-	-	-	-	42	-
18	-	-31	-	-	(23)	-
19	-	-	-	-	-	-
20	-	-	-	-	36	-
21	-	(22)	(23)	(20)	(25)	-
22	-	-	40	29	-	-
23	(20)	-	41	-	-	24
24	-	M	(21)	-	-	-
25	M	-	-	-	(22)	M
26	-	-	-29	(23)	(21)	36
27	36	-33	-	-	-	(20)
28	-	(-21)	-	-	(20)	-
29	-	-	29	-	(-22)	-
30	-	24	39	-	-	-
31	M		37	-		-

TABLE IV

Comparison of the frequency of positive correlation (Rf) between brightness data and 200-mb divergence with the frequency of tropical storms*(Sf) in the region of study from May to October 1971.

	May	Jun	Jul	Aug	Sep	Oct
Rf	8	6	14	7	13	8
Sf	4	2	8	4	6	4
Rf/Sf	2.0	3.0	1.75	1.75	2.2	2.0

Average Rf/Sf = 2.1

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*1. The term "tropical storms" in this table includes typhoons.

2. Source: U.S. Fleet Weather Central/Joint Typhoon Warning Center, 1972: Annual Typhoon Report 1972. Guam, Mariana Islands.

TABLE V

Correlation coefficients (in hundredths) of cloud brightness series vs 200-mb divergence series for 19 April - 20 December 1971. Values shown in parentheses are significant between the 90% and 95% confidence levels; values shown without parentheses are significant at the 95% level or better.

Lat./Long.	125E	130E	135E	140E	145E	150E	155E	160E	165E	170E	175E
25N	(10)	-	-	-	-	-	-	-	-	-	-
20N	14	16	-	-	17	17	-	(12)	-	-	-
15N	-	17	(11)	27	25	-	(12)	26	30	20	-
10N	-	-	(10)	(11)	-	(11)	20	19	-	-15	-
5N	-	-	-	(11)	-	(10)	-	-	-	-13	-14
Equator	-	-	(12)	-	17	(10)	-	-	-	-	(12)

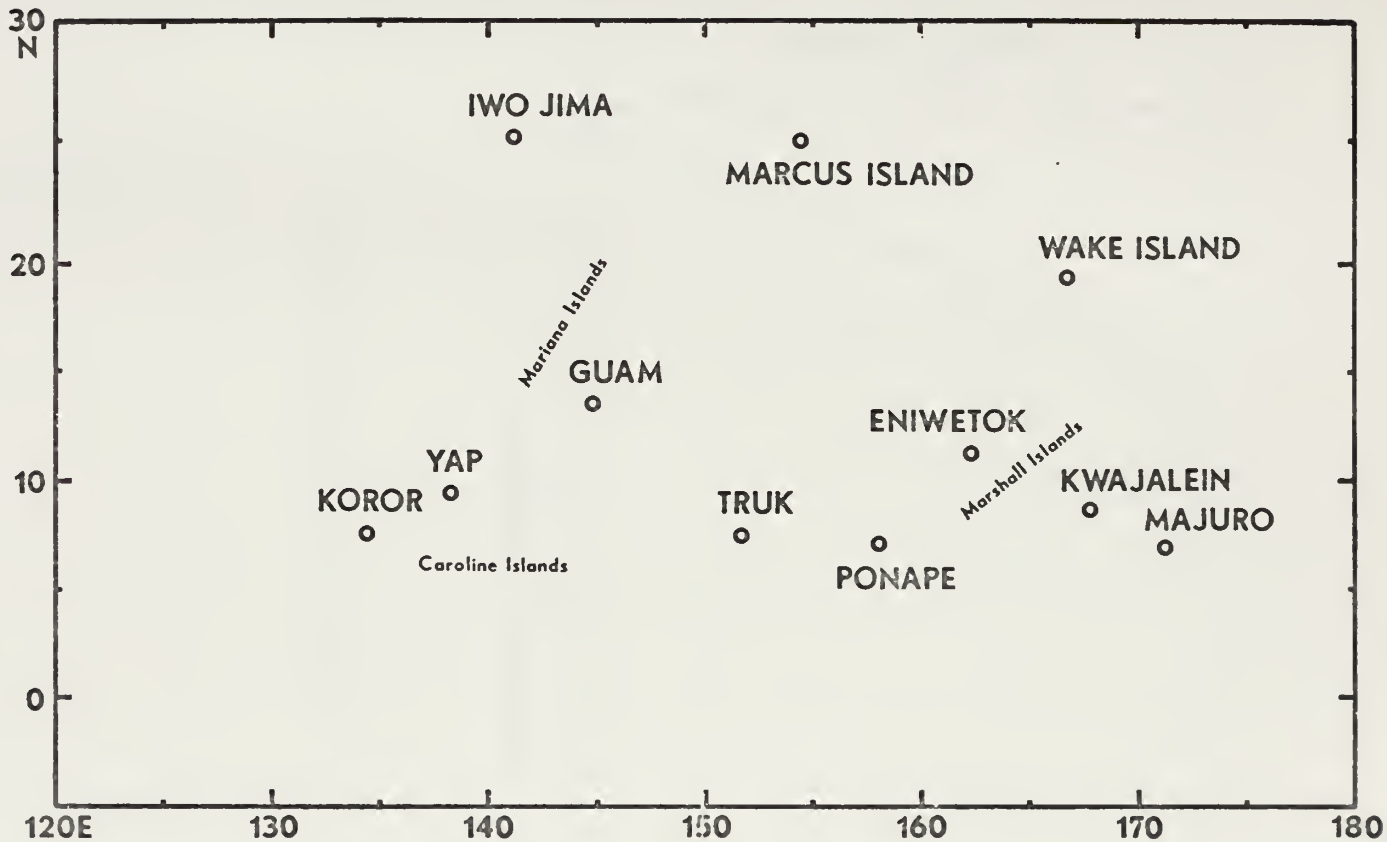

Figure 1. Region of study and observational network.

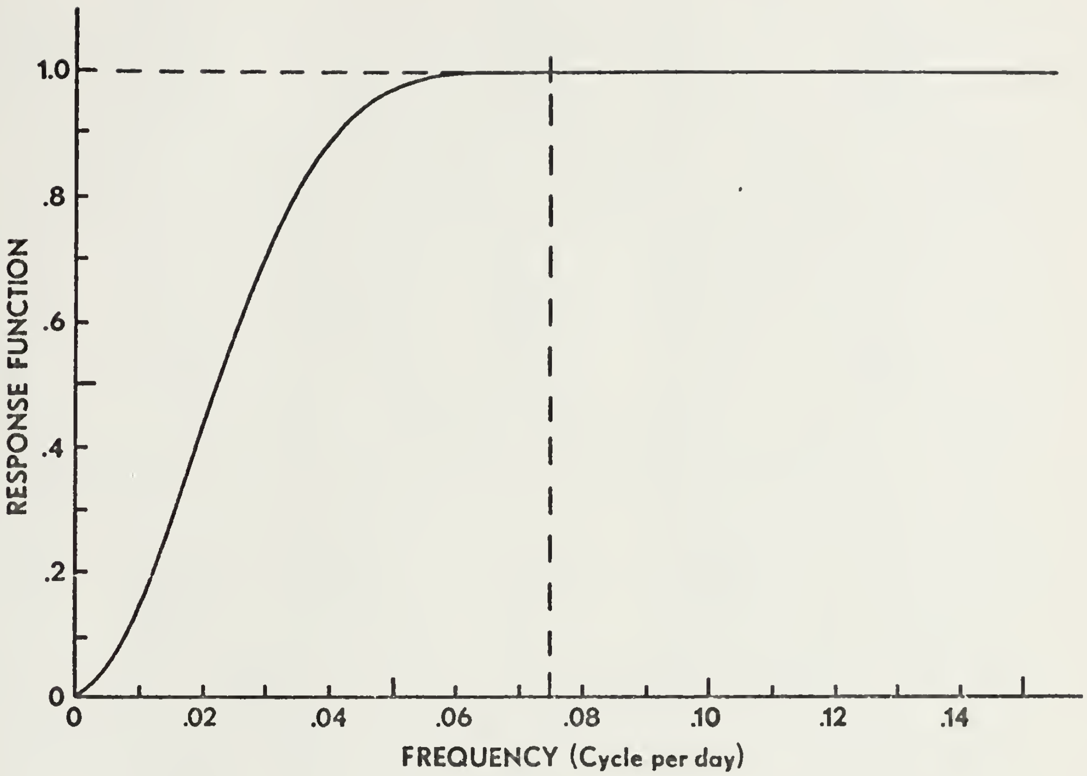

Figure 2. Spectral response function for the high-pass filter used in this study.

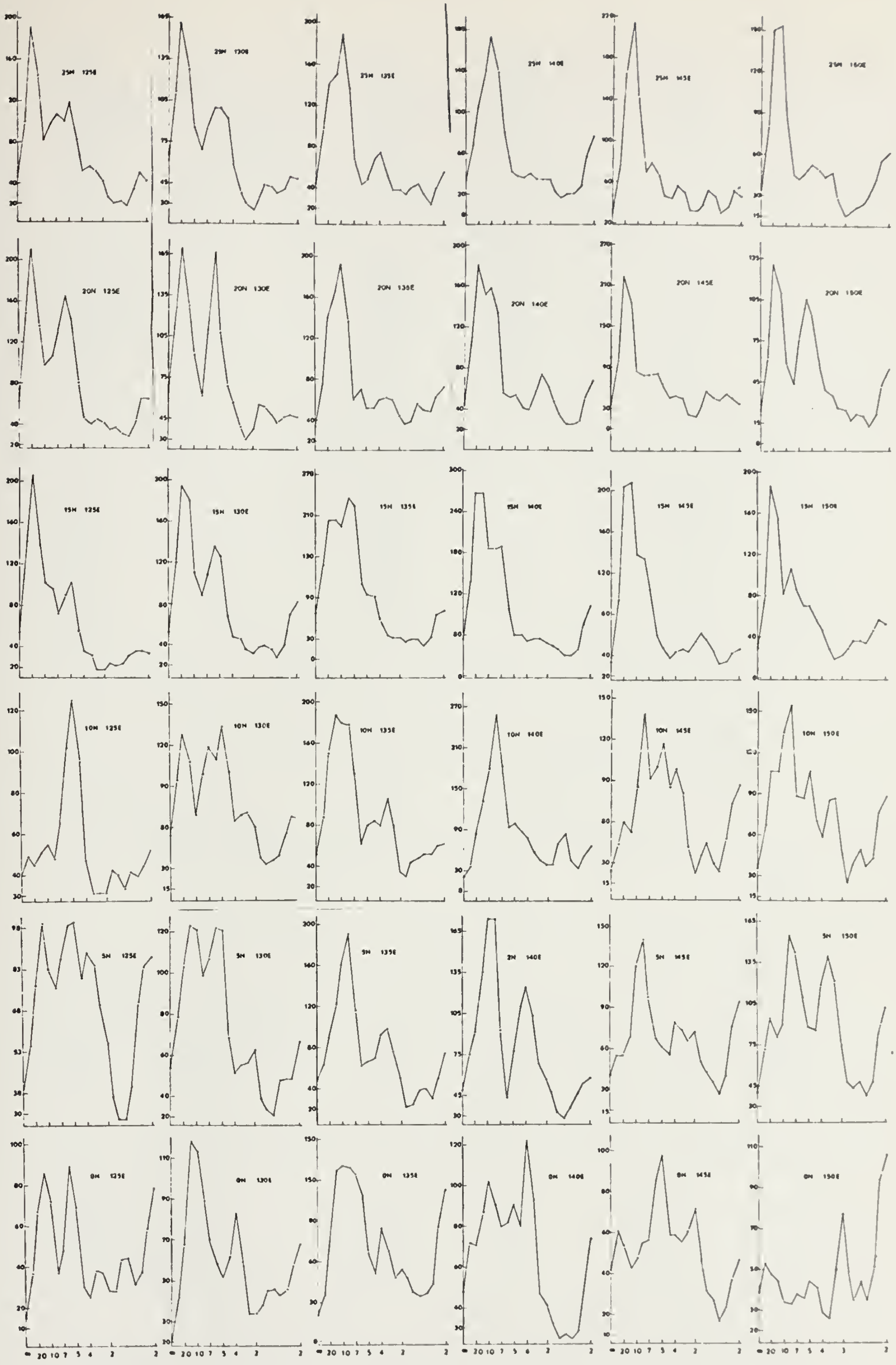

Figure 3. Power spectra of digitized satellite brightness data at the 5° x 5° grid points. The ordinate is variance per unit frequency interval (B^2 per $2\pi \times 40^{-1}$ day$^{-1} \times 10^{-1}$, where B is brightness unit with a range from 0 to 10) and the abscissa is period (days).

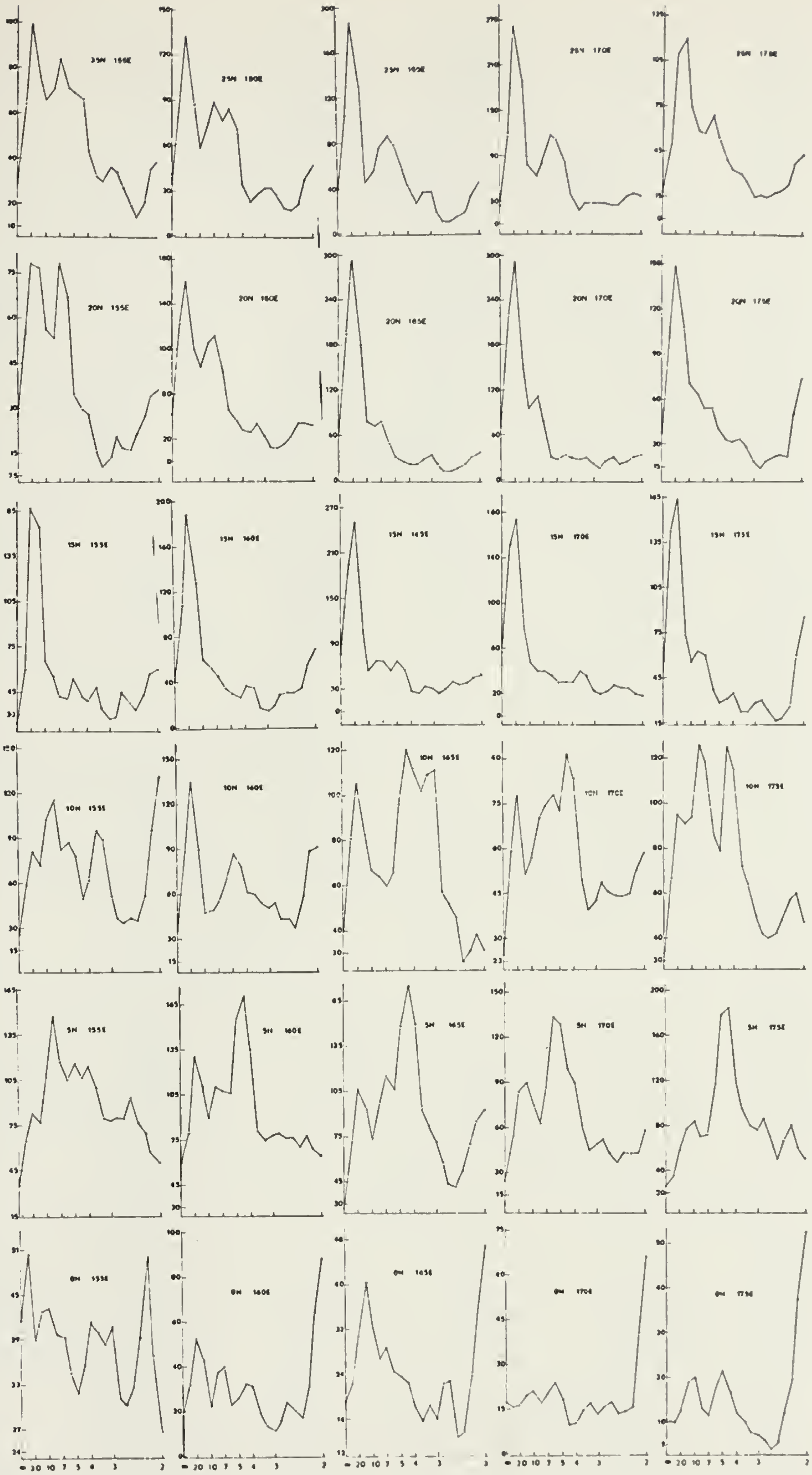

Figure 3. (continued)

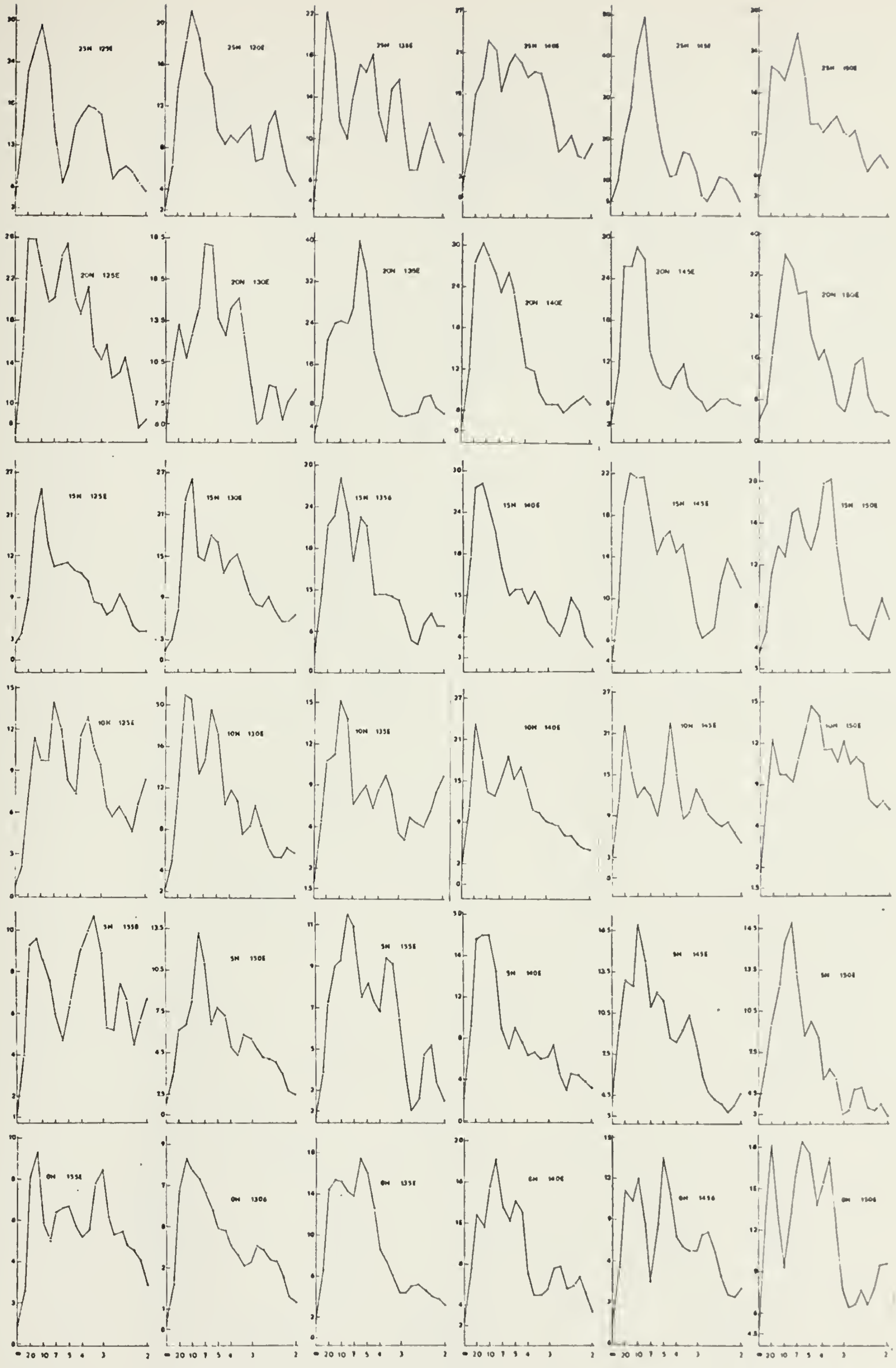

Figure 4. Same as Figure 3 except for 200-mb divergence and the unit for the ordinate is sec^{-1} per $2\pi \times 40^{-1} day^{-1} \times 10^{-12}$.

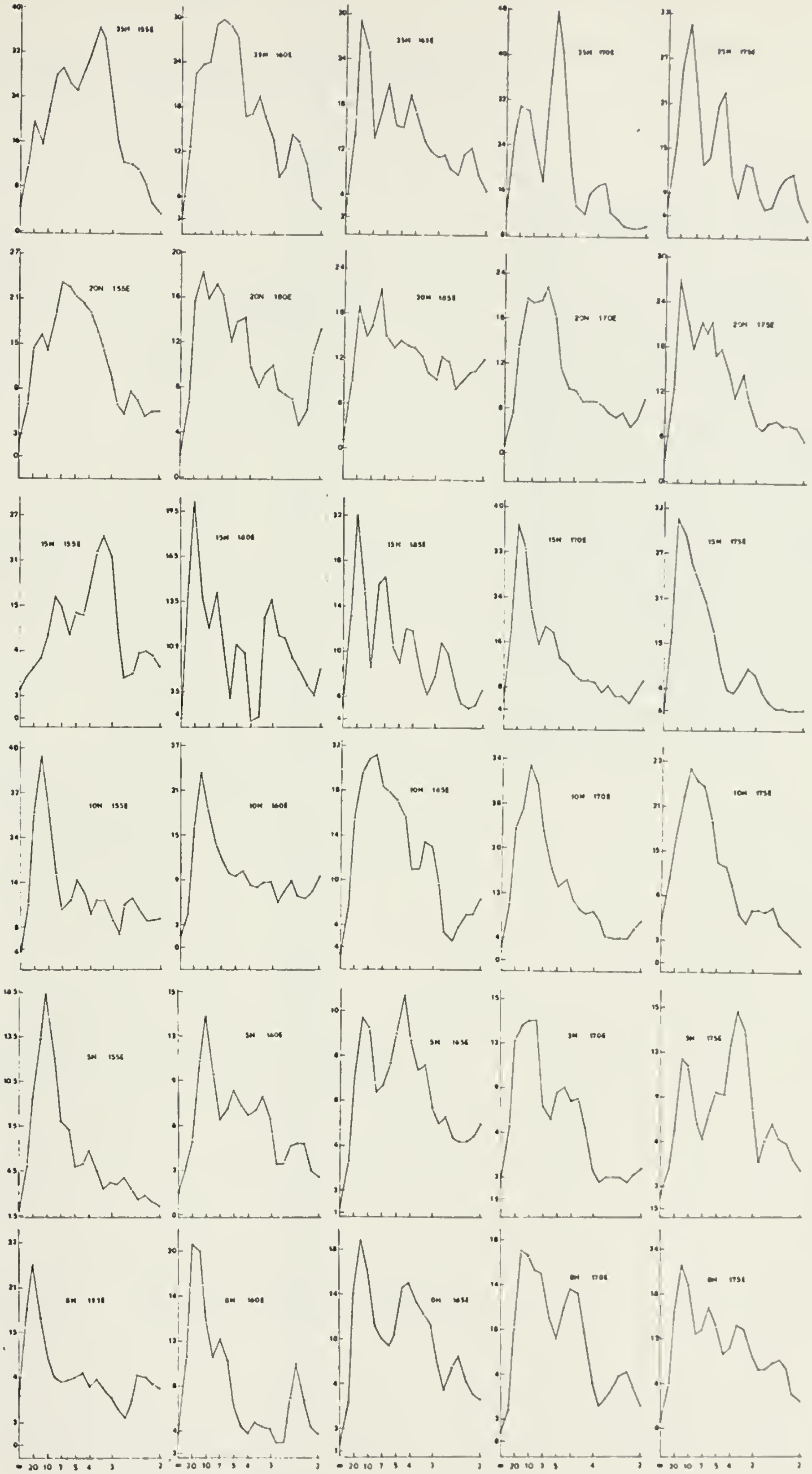

Figure 4. (continued)

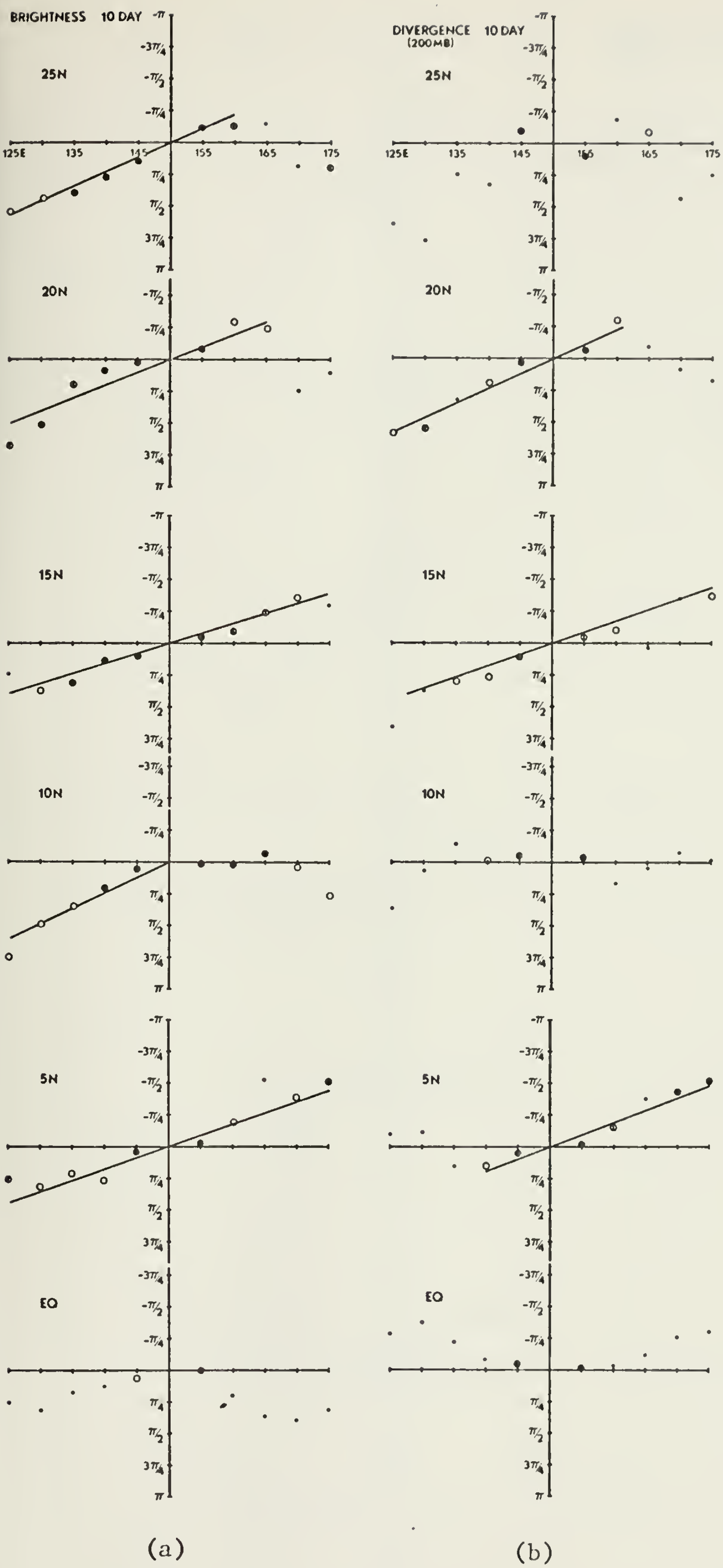

Figure 5. Interlongitude cross-spectra of (a) brightness and (b) divergence for the 10-day band. The abscissa is longitude of the series that is crossed with the base series (150E); the ordinate is phase difference with positive values indicating that the base series leads the other series. Plotting symbols indicate the significant coherence square at a given confidence level associated with each phase difference in the following way: Blackened circle, $\geq$ 99%; circle with a cross, 95-98%; open circle, 90-94%; small dot, < 90%.

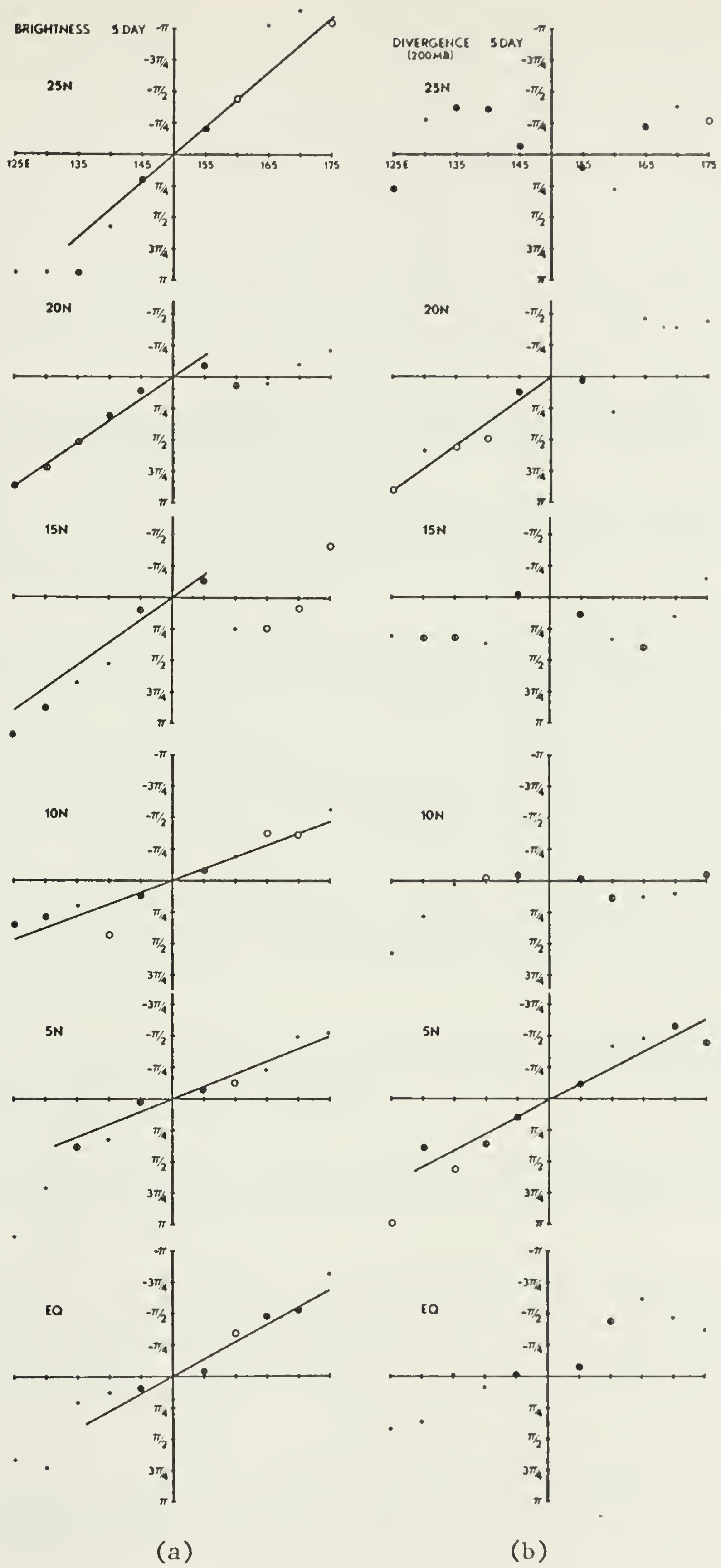

Figure 6. Same as Figure 5 except for the 5-day band.

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